APPLICATION NOTE

RAITH NANOFABRICATION

Metalens fabrication with high throughput and high precision electron beam lithography

M. Richardson[a], J.G.E. Wilbers[b], M.C. Visser[b], F. Nouvertné[c], M. Kahl[c], A.C. Zonnevylle[b]

a Raith America, Inc., 300 Jordan Road, Troy, New York 12180, USA

b Raith B.V., De Dintel 27, 5684 PS Best, The Netherlands

c Raith GmbH, Konrad-Adenauer-Allee 8, 44263 Dortmund, Germany

Introduction

Metalenses with a high numerical aperture and high efficiency have gained widespread attention in both academia and industry due to their ultra-flatness, compact size, and high-resolution imaging quality. These features qualify metalenses for potential future integration in common everyday products such as cellphones, cameras or bio-diagnostic, augmented and virtual reality components. The basic unit blocks of metalenses are typically subwavelength spaced nanostructures, such as nanofins, nanorods, and nanocylinders. These nanostructures are designed across the substrate with varying rotation angles or sizes, depending upon the design of the optical properties and specific planar position of these structures. Since high precision placement of shapes and good line edge roughness (LER) definition are essential for the fabrication of these nanostructures, electron beam lithography (EBL) has been widely used for patterning. Due to the large number, complexity, and only minimally varying rotation angles of the features, exposing such patterns poses significant challenges on EBL in terms of pattern fidelity and throughput. We demonstrate high-resolution EBL patterning with a Raith EBPG5200 Plus system, which provides high precision placement of shapes down to 80 pm accuracy with highest efficiency. To fabricate nanofins, nanorods and nanocylinders, the corresponding two-dimensional shapes in the EBL pattern are rectangles, circles and ellipses or mixtures. Traditional EBL requires a small pixel size (2 – 4 nm) to define the edge of these shapes, therefore the pattern file size is very large. In addition, the beam-on time is long. To solve this problem, we have developed a much more efficient method which circumvents the necessity to design a GDSII file at all. This method ensures precise shape placement and edge definition with minimum line edge roughness (LER) using a pattern preparation approach to create the binary exposure file algorithmically based on scripts.[1,2]

Metalens Design

To demonstrate writing metalenses with highest efficiency, a pattern was generated with a mathematic script based on the formula for the definition of a spherical lens[3]:

$$\varphi_{nf}(x,y) = \frac{2\pi}{\lambda_d}\left(f - \sqrt{x^2 + y^2 + f^2}\right)$$

Formula 1

Here, λ_d is the design wavelength, the center coordinates of each nanofin are defined by x and y and f is the focal length. Each nanofin is rotated by an angle θ_{nf} (x,y) at the given coordinates (x,y). For right-handed circularly polarized incident light, the rotations lead to a phase shift ϕ_{nf} (x,y) = $2\theta_{nf}$ (x,y) together with a polarization conversion to left-handed circularly polarized light.

The pattern consists of rectangular nanofins of 250 nm length and 95 nm height spaced a center-to-center distance of 325 nm, each with a rotation angle:

$$\theta_{nf}(x,y) = \frac{\pi}{\lambda_d}\left(f - \sqrt{x^2 + y^2 + f^2}\right)$$

Formula 2

designed for a wavelength of 532 nm. A zoomed-in area of this metalens design is shown in Figure 1.

Pattern generation

The final EBL lithography result is the combination of pattern preparation (fracturing) and exposure with the e-beam tool. In most cases the pattern is prepared as a CAD or ASCII-based data file, for example GDSII, DXF, TXL, OAS, etc. These files are subsequently fractured into less complex shapes, or primitives in a format that is compatible with the corresponding e-beam tool. The fractured binary file generated for exposure on an EBPG system is called Generic Pattern Format (GPF). A GPF can be converted by pattern preparation software from, for example, a GDSII file, or directly from an ASCII format text file which is called a GTX file for the EBPG. In this instance, the pattern was generated as a GPF binary file directly from a script.

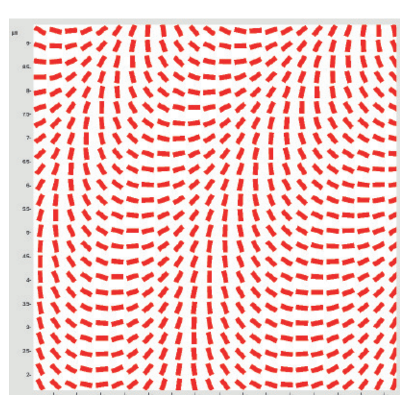

Figure 1: Example of a part of the metalens showing nanofins at various angles according to the formulas 1 and 2.

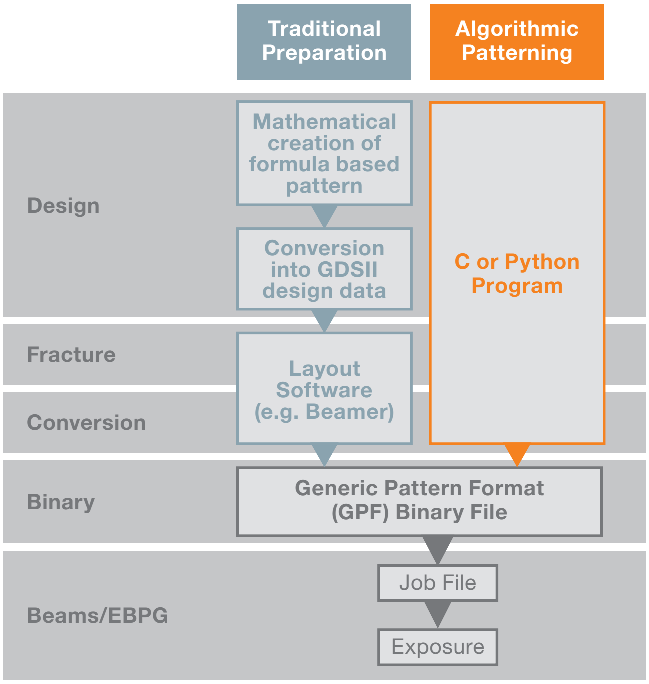

Figure 2: Workflow comparison from design preparation to exposure for the traditional method (blue gray) and the method presented here (orange). The presented method avoids the necessity of fracturing large data files.

The building blocks of metalenses are nanostructures which may have different sizes, shapes and/or rotation angles. For most applications the total size of such a metalens is typically on the order of centimeters with millions or even billions of differently oriented nanostructures[1,2]. A metalens is typically generated by a script that defines its geometry. This script creates a CAD file (e.g. GDSII) first and then must be converted by pattern preparation software to a binary exposure file (Figure 2)[3]. In traditional fracturing, a large exposure file size originates from the fact that for each individual nanofin with different angle orientation, a unique composite of trapezoids must be created. For billions of nanofins, this is a huge amount of data, and a potentially time-consuming and data-intensive process.

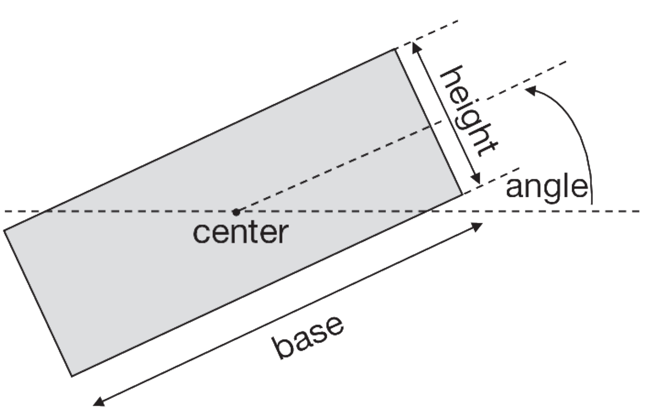

Figure 3: Definition of a cube shape; the angle rotation can be changed in the nano degree regime

A major advantage of generating the GPF file directly from a script is that each nanofin may be defined as one single and consistently-formed shape and not sub-divided into individually-defined trapezoids that would drastically increase complexity and EBL process time. In addition, trapezoids can cause artifacts in the nanofin when rotated at an angle because uniform placement of beam shots is not possible with composite trapezoids. In the case of the nanofins fractured as a single cube shape (Figure 3) the placement of the beam shots remains uniform with varied rotation (Figure 4). The method also works for all EBPG basic shapes such as trapezoids, circles, rings, ellipses, lines, polygons, paths, etc.

Example scripts are delivered as standard with the EBPG5200 Plus BEAMS software package that provide the definitions needed to create the GPF file directly from user script. This method eliminates the need to create a design layout file (e.g. GDS II) and perform a subsequent conversion to the GPF format, which can be complex and CPU-intensive for large patterns with millions or even billions of shapes, and gives the programmer control over the fracturing strategy. The size of the GPF file is limited only by the available disk space.

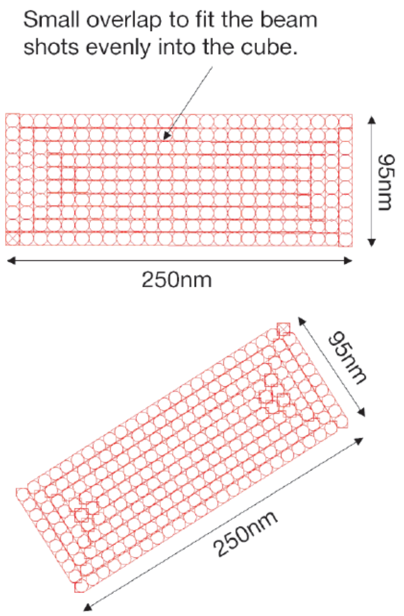

Figure 4: Two cubes without rotation (above) and under rotation (below). The distribution of the beam shots is homogenous due to the smooth mode and uniform for both.

Programming the EBPG GPF Data Format in C

The pattern file was generated as a binary EBPG Generic Pattern Format (GPF) file from a C script compiled and executed on an EBPG workstation configured in the Red Hat Enterprise Linux 7-based BEAMS environment.

By specifying a subfield size that is a multiple of the 325 nm center-to-center shape spacing, we avoid fracturing shapes across subfield boundaries. The subfield size was specified at 3.25 µm and the main field size was set at 487.5 µm, well within the 1048.576 µm maximum field size for a 20-bit EBPG 5200 Plus at 100 kV.

The pattern was designed as a circular lens using floating field placement in a spiral configuration beginning in the center and working outward (Figure 5). Fields are exposed in the order that they were created and listed in the GPF file. The subfields were configured in a meander pattern within their respective fields. The resulting scalable design could be easily modified to evaluate parameters such as beam step size, wavelength or focal length by creating and exposing smaller-diameter patterns before committing to the full-sized pattern.

Optimum throughput for both pattern file generation and writing, as well as metafin fidelity, depend on algorithmic creation of whole shapes that are not fractured across field boundaries.

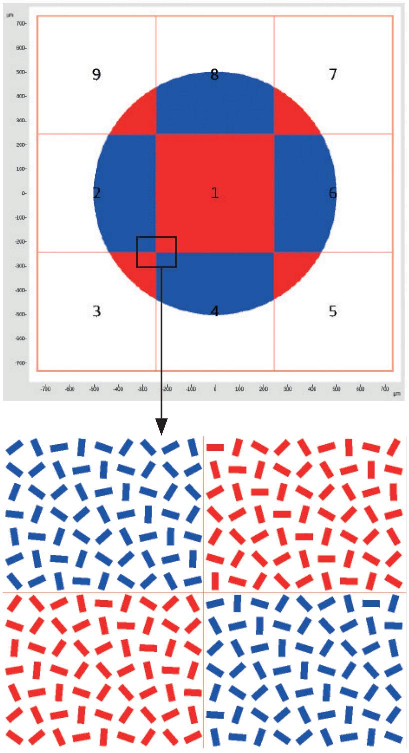

Figure 5: Pattern image showing a metalens with 1 mm diameter. The contrasting colors illustrate the fields which are written in spiral mode from inside to outside. The field size was chosen in such a way that the nanofins are not on the field boundaries

The basic shape type used for the metafins in this design is called a cube: a rectangle defined by its base, height, and center coordinates, and rotation angle. In this pattern, the cubes have uniform base and height, but varying rotation depending on the center coordinates according to formula 2.

The beam shots are placed using the pattern generator's "smooth mode", which ensures uniform dose distribution and preserves the fidelity of the nanofins with regard to precise edge definition because the beam shots are evenly distributed regardless of shape rotation (see Figure 4). In addition to the smooth mode, the cubes are filled in spiral-in mode, a specific and unique shape filling mode, which reduces line edge roughness (LER).

To analyze the impact of beam step size (BSS) on fidelity and write time, exposures were performed at three different beam step sizes: 10 nm, 20 nm and 40 nm.

File Generation

As said before, this method to create a GPF file from a script can be utilized for any of the shapes supported by the EBPG pattern generator (e.g. circle, ellipse, etc.) The effect of metafin shape type on file size is dependent on the number of parameters required to describe each instance of the shape in the GPF file. At a minimum, shapes are defined by primitives expressing their coordinates and dimensions, and any rotation angle. File generation time is minimally dependent on the shape type, and (aside from the obvious CPU speed and file I/O overhead) more so on the calculations required to define, orient, and place the shapes to meet pattern design requirements.

Lens Diameter (µm)	Number of Metafins	Number of Occupied 487.5 µm Main Fields	GPF File Generation Time (hh:mm:ss.s)	GPF File Size (MB)
100	74,357	1	00:00:00.92	1.22
200	297,417	1	00:00:03.64	4.89
500	1,858,945	5	00:00:22.45	30.57
1,000	7,435,733	9	00:01:32.99	122.26
2,000	29,742,853	21	00:06:04.52	489.00
5,000	185,893,285	101	00:37:55.66	3,056.80
10,000	743,572,201	373	02:33:04.13	12,224.55
20,000	2,974,289,097	1,401	10:17:03.06	48,898.42
50,000	18,589,305,877	18,589	105:21:32.45	305,614.22

Table 1: GPF file statistics for cube-based circular metalenses ranging from 100um to 20mm in diameter executed on a 2.60 GHz Intel Xeon Silver 4112 CPU

As can be seen from Table 1, the size of the GPF file and the time necessary to generate it both follow a similar curve to the number of metafins within its diameter. Analyzing the data provides some ability to predict file size and generation time for larger diameter patterns. As the lens diameter doubles, the number of metafins, the GPF file size and the file generation time each increase by a factor of four.

Exposure Results

The test patterns were exposed on a Silicon wafer coated with 100 nm ZEP520 A (1:2 diluted with anisole, spin-coated at 2000 rpm for 1 minute, baked for 3 minutes at 170° C). Exposure was performed with an EBPG5200 Plus at 100 kV at a dose of 260 µC/cm^2. The sample was developed at room temperature for 30 seconds in n-amyl acetate followed by a 30-second rinse in isopropanol and dried under N2 flow.

Diameter (mm)	Pattern Elapsed Time [mm:ss]
1	00:34
2	02:15
10	56:19

Table 2: Pattern exposure times for three different metalens diameters. The nanofins have a size of 95 nm by 250 nm and a spacing from center-to-center of 325 nm. The beam step size is 20 nm and the beam current 80 nA for a frequency of 77.49 MHz. Exposures were performed on an EBPG5200 Plus at 100 kV with the EBPG Firebird feature.

In order to achieve satisfactory line edge roughness in general, a small beam step size and thus small beam current should be selected. This increases the exposure time significantly. However, for the nanofins defined with smooth and spiral fill-in mode a larger beam step size and beam current can be used while maintaining excellent minimum LER and without reducing pattern quality. The enormous benefit is the improved throughput which is a major requirement for the implementation of metalenses into industrial device fabrication.

To show that pattern quality can be maintained with a small or large beam current, metalenses were exposed at a large beam current of 80 nA, as well as at smaller beam currents of 5 nA and 10 nA.

The corresponding throughput times for exposures of 1 mm, 2 mm and 10 mm metalenses with a beam step size of 20 nm and a beam current of 80 nA with EBPG Firebird technology are given in Table 2.

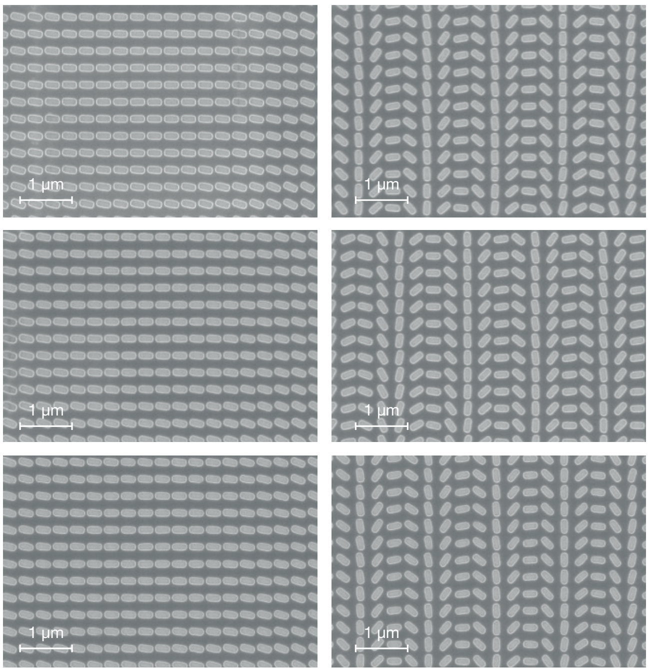

Figure 6: SEM images of the metalens pattern in 100 nm ZEP520 A resist on a Silicon substrate exposed with (a) 5 nm BSS and 5 nA, (b) 10 nm BSS and 20 nA and (c) 20 nm BSS and 80 nA. The metalens diameter for these exposures was 100 µm. Images on the left side were taken in the center, and images on the right were taken on the edge to show the fidelity over the whole pattern.

Firebird is a new specific data processing acceleration technology, that adds remarkable computational power and – depending on the specific lithography parameter sets – can significantly speed up the total lithography process.

Figure 6 shows SEM images of the metalenses exposed with different beam currents (5 nA, 20 nA and 80 nA) taken with a ZEISS SEM. The images were taken in the center and at the edge of the metalens, respectively. One can see that it is possible to expose the metalens with high pattern fidelity at high beam current without losing resolution. This demonstrates the strength of this high-resolution method.

Conclusion

A method for algorithmic pattern preparation and high-throughput exposure of metalenses with high fidelity was demonstrated on a 100 kV EBPG Plus system with Firebird data processing acceleration technology. The preparation of a generic pattern file for EBPG directly from a script avoids the fracturing of large data files which is very time consuming and sometimes even impossible for patterns consisting of millions or billions of shapes. The creation of a design layout (e.g. GDSII) and subsequent conversion to the GPF format is avoided. The programmer controls the fracturing strategy in a way that contains the shapes within subfield and field boundaries, maintaining fidelity. The only limitation for the GPF file size is the available disk space.

As an example, nanofins in the shape of rectangles, with a width of 95 nm, a length of 250 nm and a distance of 325 nm from nanofin center to nanofin center, at various different angles were exposed as metalenses with 10 mm diameter. The elapsed exposure time was 56 minutes and 19 seconds for a metalens with a diameter of 10 mm at 80 nA beam current and 20 nm BSS. Such a high throughput is possible because with this high-resolution mode method, larger beam step sizes and thus higher beam currents are possible while maintaining uniform nanofin quality over the pattern area.

References

1 Colburn, S., Zhan, A. and Majumdar, A., “Verifocal zoom imaging with large area focal length adjustable metalenses,” Optica 5 (7), 825-831 (2018).

2 She, A. Zhang, S., Shian, S., Clarke, D.R., and Capasso, F., “Large area metalenses: design, characterization, and mass manufacturing” Optics Express 26 (2), 1573-1585 (2018).

3 Khorasaninejad, M., Chen, W. T., Devlin, R. C., Oh, J., Zhu, A. Y., Capasso, F., “Metalenses at visible wavelengths: Diffraction-limited focusing and subwavelength resolution imaging,” Science 352 (6290), 1190-1194.

Raith GmbH	Konrad-Adenauer-Allee 8, PHOENIX West, 44263 Dortmund, Germany phone +49 231/95004-0, fax +49 231/95004-460, e-mail: sales@raith.com, website: www.raith.com
Raith America Inc.	1377 Long Island Motor Parkway, Suite 101, Islandia, New York 11749, USA phone +1 631 738 9500, fax +1 631 738 2055, e-mail: sales@raithamerica.com
Raith Asia Ltd.	Two Chinachem Exchange Square, No. 338 King‘s Road, Floor 11, Unit 03, North Point, Hong Kong phone +852 2887 6828, fax +852 2887 6122, e-mail: sales@raithasia.com
Raith China Ltd.	Room 1409, Tower B, Techart Plaza, No.30 Xue Yuan Road, Haidian District, 100083 Beijing, P.R.China phone +86 10 828679 22, fax: +86 10 828679 19, e-mail: sales@raithchina.com
Raith India Pvt. Ltd.	Sri Krishna Complex, No 36, 2nd Floor, Opp. Mother Theresa School, M. E. S. Ring Road, Bangalore 560054, India phone +91 80 2838 4949, Fax +91 80 2838 4949, e-mail: sales@raithindia.com